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A TEST OF A CLIMATIC INDEX OF DUNE MOBILITY USING MEASUREMENTS FROM THE SOUTHWESTERN UNITED STATES

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ABSTRACT

The climatic index of dune mobility developed by Lancaster (1988) has been applied to a variety of different environments. The index is, however, untested and unverified. We tested the index by comparison of values of the dune mobility index calculated from climate data with rates of sand transport measured at three stations in Arizona and New Mexico over the period 1985 to 1997.

Our results show that changes in measured rates of sand transport closely parallel temporal changes in the dune mobility index. The mobility index is, however, a relatively poor predictor of the magnitude of actual sand transport on a year-to-year basis. This discrepancy is probably due to the fact that sand transport rates at these sites are strongly influenced by vegetation cover, the state of which may lag changes in annual precipitation. There is, however, a good relation between the mean annual mobility index and mean annual rates of sand transport. This indicates that the dune mobility index is a valid predictor of the long-term state of the aeolian system and can be used confidently for the purposes for which it was originally intended. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: sand transport; dune mobility index; climatic gradient

INTRODUCTION

Vegetation-stabilized dunes and sand sheets are an important component of the landscape in semi-arid and sub-humid regions (e.g. the Kalahari, central Australia, north-central Negev Desert, southern Sahara, and the Great Plains of the USA). Many of these areas of aeolian deposits exhibit a range of states of dune mobility, ranging between those completely stabilized by vegetation (inactive, relict or dormant dunes) to fully active or mobile dunes where vegetation cover plays a minor role in dune dynamics and morphology (Thomas and Tsoar, 1990). Between these end members lie a vast range of intermediate states in which vegetation plays some role in dune dynamics and some part of the dune landscape is covered by vegetation (Lancaster, 1988; Muhs and Maat, 1993; Wiggs *et al.*, 1995; Wolfe, 1997). In the absence of significant impacts by humans and grazing animals, the range of states of dune mobility generally follows a climatic gradient in which the mobility of dunes is determined by the ratio between wind energy for sand transport and the amount of vegetation cover. In some areas, temporal changes in dune state have been related to changes in climatic conditions as vegetation cover on dunes responds to drought cycles (Thomas and Tsoar, 1990; Gaylord and Stetler, 1994; Muhs and Holliday, 1995; Bullard *et al.*, 1997; Wolfe, 1997).

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A number of climatic indices of dune mobility have been developed, based on the premise that, on time scales of years to decades, aeolian activity in inland dune areas is a function of the ratio between wind energy (sand transport potential) and vegetation cover (sediment mobility), with the amount of vegetation cover being determined by the effective precipitation (Talbot, 1980; Ash and Wasson, 1983; Wasson, 1984; Lancaster, 1988). Of these indices, the one developed by Lancaster (1988) has been the most widely adopted (e.g. Muhs and Maat, 1993; Stetler and Gaylord, 1996; Bullard *et al.*, 1997; Wolfe, 1997). This index provides a measure of sand mobility (M) as a function of the ratio between the annual percentage of the time the wind is above the threshold for sand transport (W) and the effective annual precipitation (P/PE), where PE is potential evapotranspiration calculated using the Thornthwaite method (Thornthwaite and Mather, 1957):

$$M = W/(P/PE)$$

Critical values of M are: < 50, dunes inactive; 50–100, only crests of dunes active; 100–200, dunes active, but interdunes and lower dune slopes are vegetated; and > 200, dunes fully active.

The Lancaster index has been qualitatively tested by comparison of the above limiting values of the index with the state of dune activity observed on aerial photographs, and appears to perform quite well (Muhs and Maat, 1993). It is, however, unclear if the index is a good predictor of the amount of aeolian activity and sand transport rates in vegetated dune environments and whether it can therefore be used to predict quantitatively the state of aeolian systems.

A quantitative assessment of the index requires that climatic parameters and physical measurements of sand transport rates are available for long periods of time at the same location. Typically, field measurements of sand transport rates are made for short periods (e.g. tens of minutes to hours) and are not available on a multi-year basis. One such data set does, however, exist in the form of measurements by the United States Geological Survey (USGS) at their Geomet (geometeorological) stations in the southwestern United States. This paper performs a test of the Lancaster dune mobility index using data for three stations in this region, and evaluates the performance of the index as a quantitative predictor of the state of aeolian systems on an annual to decadal timescale.

DATA SOURCES AND METHODS

The primary source of data for this analysis was the USGS Geomet stations located at: (1) Jornada Experimental Range, New Mexico (Chihuahuan Desert); (2) Gold Spring, Arizona (Colorado Plateau Desert); and (3) Yuma, Arizona (lower Sonoran Desert) (Figure 1). The stations were set up in the 1970s under the USGS Desert Winds Project, designed to permit remote monitoring of aeolian processes (McCauley *et al.*, 1984; Breed and Reheis, 1999; Breed, 1999). Each station used in this study is equipped with anemometers at three heights (1·2, 2·7 and 6·1 m), a wind vane at 6·1 m, temperature and humidity sensors at 1·2 and 6·1 m, and a tipping bucket rain gauge. Transport of sediment by wind is monitored by BSNE sand traps (Fryrear, 1986) mounted at 0·05 or 0·15 m, 0·50 m and 1·0 m, together with a Sensit piezo-electric sand transport sensor at 0·05 or 0·15 m above the surface. Full details of the instrumentation and operation of the stations are given in Tigges *et al.* (1999).

With the exception of the BSNE traps, all sensors are scanned on a 1 s interval, and 6 min averages of the anemometer, wind vane and Sensit readings, together with 12 min average temperature, as well as hourly humidity and precipitation are uploaded via GOES satellite each hour. The BSNE traps are emptied on a nominal weekly schedule and the collected sediment is weighed later.

These data permit calculation of dune mobility indices on an annual basis for comparison with measured mass transport rates for the same locality. The most complete data sets for sand transport cover the period 1986 to 1997, so these years were used for this study.

The mobility index was calculated using data for annual precipitation, mean monthly temperature, and percentage of the time the wind was above sand transport threshold. The sand transport threshold and the Thornthwaite potential evapotranspiration were calculated using the same program and threshold equation as used by Muhs and Maat (1993). A mean surface particle size of 300 μm was adopted for all three sites, for

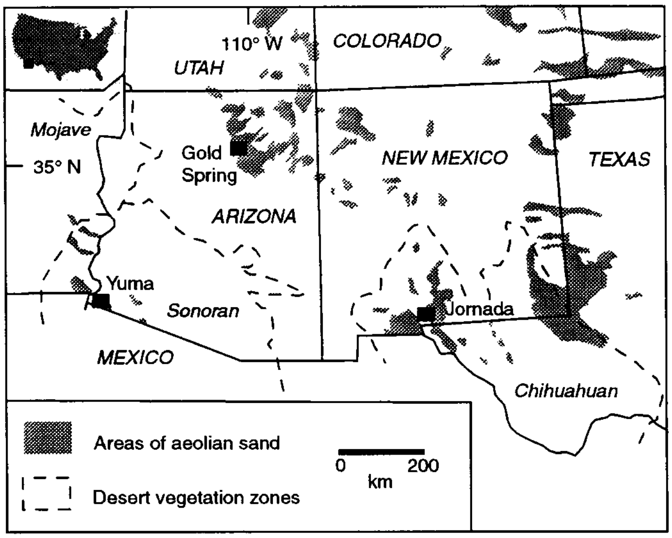


Figure 1. Location of the Geomet stations used in this study

comparison with data in Muhs and Maat (1993), and gave a threshold wind speed of 5·85 m s^{-1} at a height of 6·1 m. Annual rates of sand transport were estimated by integrating the annual total mass of sand caught in each trap with respect to trap height. This eliminated problems with changes in the height of the bottom trap over time due to scour and resetting of the trap to different heights by station maintenance personnel to correspond with changes in Sensit height relative to the sand surface. The sand trap data are the least reliable of the data sets used in this study, as a result of issues of trap efficiency, collection schedules and placement of traps, especially at Jornada. The sand transport rates given below must therefore be considered to be minimum values. The interpretation of the Sensit data was considered uncertain as a result of instrument calibration problems and these data were not used in this study.

THE GEOMET SITES

All of the stations used in this study are located on sparsely to moderately vegetated sand sheets in semi-arid to arid areas of Arizona and New Mexico (Figure 1). Table I summarizes important climatic parameters for each station. The Jornada station is located on the USDA/ARS Jornada Experimental Range in southern New Mexico. The site lies on a sandy plain in the northern Chihuahuan Desert. Vegetation at this site is dominated by two species of shrub (Musick and Gillette, 1990)–mesquite (*Prosopis gladulosa*) and snakeweed (*Gutierrezia sarothrae*)–together with a perennial bunch grass dropseed (*Sporobolus* spp.). The mesquite shrubs trap sand to form small nebkhas. The area surrounding the station is lightly grazed. The Yuma station

Table I. Summary of mean annual climatic parameters and sand transport rates for the study sites for the period 1986–1997

Station	Mean annual precip. (mm)	Mean annual temp. (°C)	Mean annual *PE* (mm)	Mean annual *W* (%)	Mean annual sand transport rate (kg m^{-1} a^{-1})	Mean Annual Mobility Index (*M*)
Jornada	212	15·8	869	8·30	18	37
Yuma	66	23·5	1286	7·24	504·2	213
Gold Spring	114	12·5	730	14·75	51·4	133

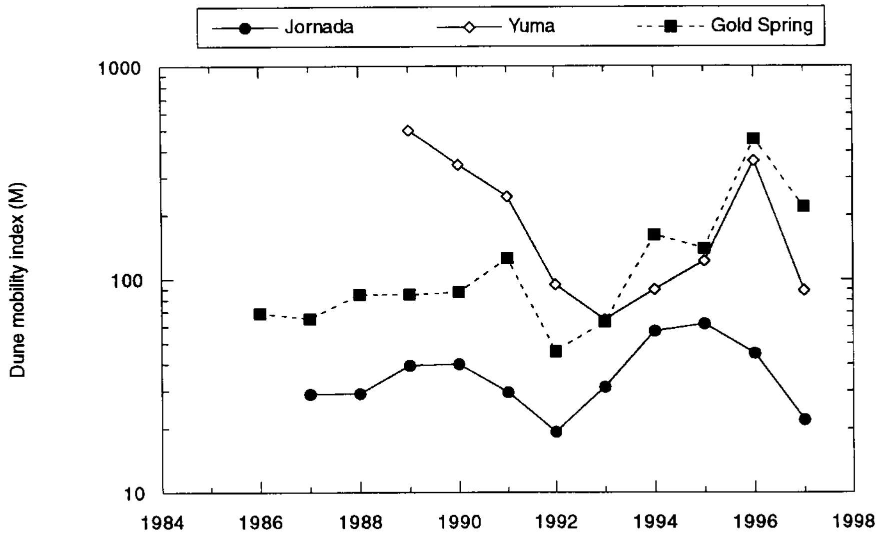


Figure 2. Temporal variations in the calculated dune mobility index (*M*)

is located on a sand sheet in the lower Sonoran Desert. The vegetation at this site is dominated by creosote bush (*Larrea tridentata*), white bursage (Ambrosia dumosa) and big galleta grass (*Hilaria rigida*), but many ephemeral herbs grow after heavy winter rains (Musick and Gillette, 1990). The area around this site is not grazed. The Gold Spring station is located in an area of vegetated linear dunes on the Moenkopi Plateau of northeastern Arizona. The site lies in the Colorado Plateau Desert. Vegetation at the site is complex, and is dominated by broom snakeweed (*Gutierrezia sarothrae*), galleta grass (Hilaria jamesii), yucca (*Yucca* sp.), and needle and thread grass (*Stipa comata*), with scattered black grama grass (*Bouteloua eriopoda*), rice grass (*Oryzopsis hymenoides*) and *Ephedra* sp. Sandhill muhly (*Mulhenbergia pungens*) dominates the linear dune crests. Grazing in the vicinity of this site is moderate.

RESULTS

Dune mobility index

The three stations exhibit a wide range in mean annual values of the dune mobility index (*M*) for the period 1986–1997, from 37 at Jornada to 133 at Gold Spring, and 212 at Yuma. Gold Spring is the windiest site, with a *W* value of 14·75 per cent, which results in an intermediate *M* value, and Yuma is the least windy ($W = 8{\cdot}23$ per cent). The high *M* value at Yuma is the result of the low mean annual precipitation (66 mm) and the high mean annual temperature (23·54°C). The low *M* value at Jornada is the result of the high annual precipitation (212 mm).

All three stations exhibit significant variations in the magnitude of the dune mobility index (*M*) over the period studied (Figure 2). At Jornada, the index varies between a low of 19 in 1992 and a high of 62 in 1995. Values for *M* at Yuma exhibit a very wide range from a high of 502 in 1989, falling to a low of 64 in 1993, and rising again to 361 in 1996. Dune mobility index values at Gold Spring fluctuate about a mean of 78 in the 1980s, rise to 126 in 1991, and fall to low levels (46–63) in 1992 and 1993, before rising to an all-time high of 454 in 1996. For the period of record, coefficients of variability of the mobility index are 0·37 at Jornada, 0·74 at Yuma and 0·84 at Gold Spring.

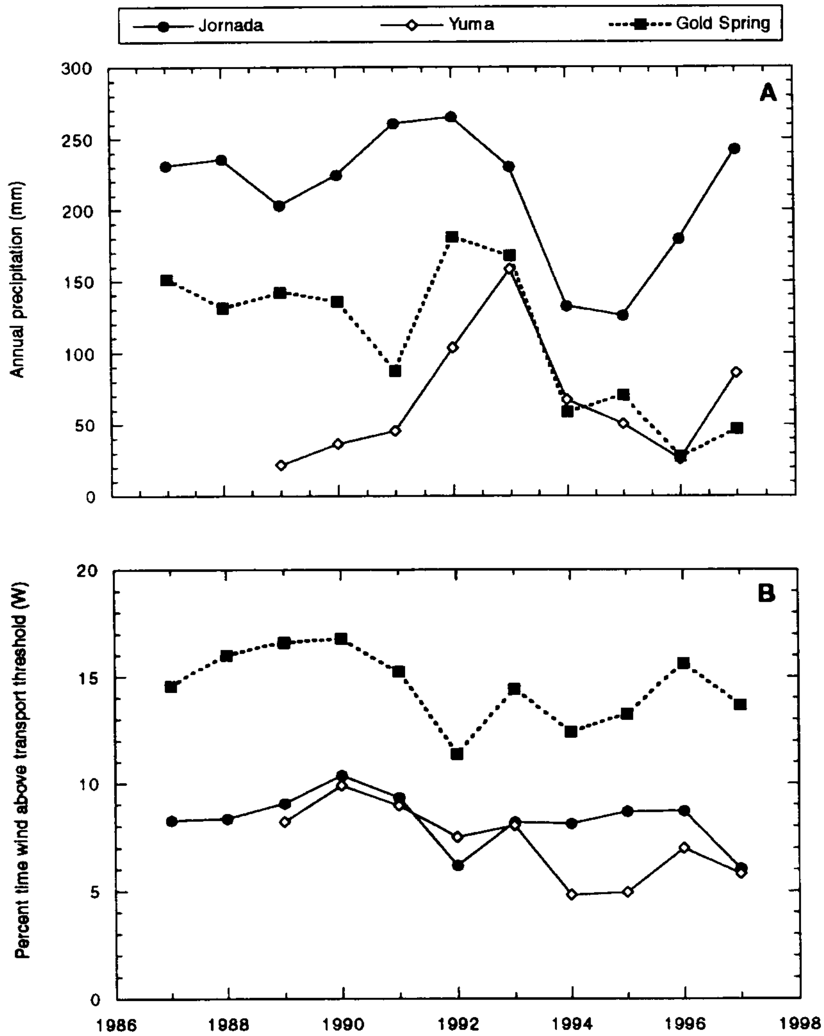


Figure 3. Temporal variations in (A) annual precipitation and (B) percentage of time wind is above threshold (*W*)

Values of the dune mobility index exhibit similar temporal patterns at the different stations (Figure 2). Values of *M* are relatively high in the late 1980s and early 1990s and decline to a minimum in 1992 or 1993 at all stations. There is a rise in mobility index values in the mid-1990s, reaching a peak in 1995 or 1996.

Variations in the dune mobility index appear to be driven primarily by changes in precipitation totals from year to year. During the period of study, the coefficient of variation (*CV*) of mean annual temperature at each station was 0·03–0·06 and the *CV* for the percentage of the time the wind was above threshold (*W*) varied between 0·12 at Gold Spring and 0·24 at Yuma. These contrast with coefficients of variability of precipitation that range from 0·22 at Jornada, through 0·47 at Gold Spring to 0·66 at Yuma. Comparison of the record of the dune mobility index with that for annual precipitation at the stations reveals a striking degree of parallelism (Figure 3). Periods of wet years are always times of low mobility index. Likewise, dry years result in high *M* values. There is no consistent relation between precipitation and windiness.

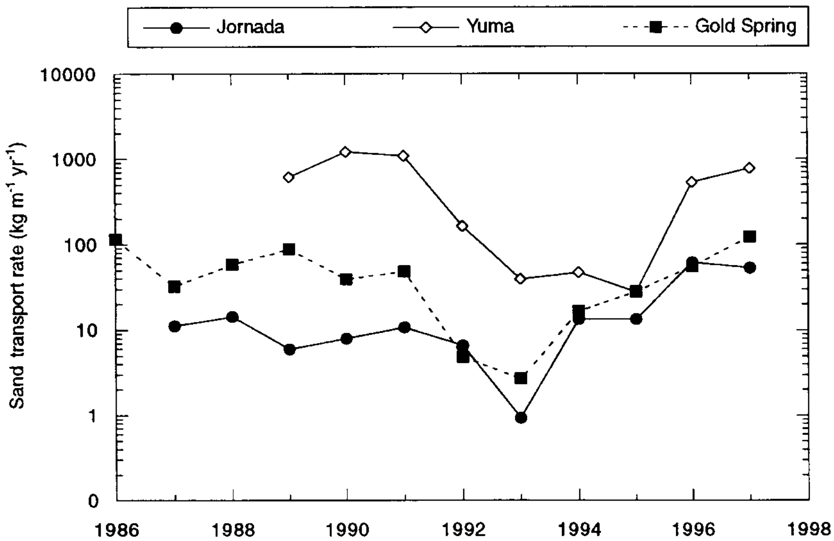


Figure 4. Temporal variation in annual rates of sand transport

Sand transport rates

Mean annual sand transport rates vary over an order of magnitude from the lowest rates of 18 kg m^{-1} a^{-1} at Jornada to 51·4 kg m^{-1} a^{-1} at Gold Spring, and 504·2 kg m^{-1} a^{-1} at Yuma. The rank order of the stations follows the rank of mobility index values and mean annual precipitation at the sites.

Figure 4 shows the temporal variation in sand transport rates over the period of study. Annual sand transport rates at Jornada fluctuate about a mean of 10 kg m^{-1} a^{-1} during the period 1987–1992, then drop to negligible values (0·94 kg m^{-1} a^{-1}) in 1993. They then rise again to 13·5 kg m^{-1} a^{-1} in 1994–1995. The higher values for sand transport rates in 1996 and 1997 (61·9 and 53·7 kg m^{-1} a^{-1} respectively) are the result of a change in the location of the sand trap within the station enclosure effective in late 1995. The original location was apparently sheltered by growth of a small nebkha upwind. Sand transport rates at Gold Spring follow a similar pattern, but at a generally higher magnitude. From 1986 to 1991, sand transport rates fluctuate about a mean of 55·7 kg m^{-1} a^{-1} with a high of 86 kg m^{-1} a^{-1} in 1989 and a low of 32·5 kg m^{-1} a^{-1} in 1987. There is a sharp decline in sand transport rates to low values of 4·9 and 2·7 kg m^{-1} a^{-1} in 1992–1993, followed by a steady rise to a peak of 123·4 kg m^{-1} a^{-1} in 1997. At Yuma, sand transport rates are very high (>1000 kg m^{-1} a^{-1}) in 1990–1991, and decline sharply to very low values in 1993 to 1995 (39·5–27·9 kg m^{-1} a^{-1}). Sand transport rates rise again in 1996–1997, but reach values that are only 50–75 per cent of those reached in 1990–1991.

There are some striking parallels between the record of measured sand transport rates at the three stations (Figure 4). The late 1980s are characterized by high rates of sand transport, whereas the period 1992–1993 exhibits the lowest rates in the period of record. Sand transport rates then recovered during 1996–1997. It is interesting to note that, at Gold Spring, sand transport did not recover from the low rates of 1992 and 1993 until 1995.

Relations between the mobility index and measured sand transport rates

Comparison of Figures 2 and 4 shows that the temporal patterns of the dune mobility index calculated from meteorological data and the actual rate of sand transport measured at the same site vary in a quasi-synchronous fashion. In general, low rates of sand transport correspond to periods when the mobility index values are low (e.g. 1992–1994). A rise in sand transport almost always is paralleled or led by an increase in the dune mobility index.

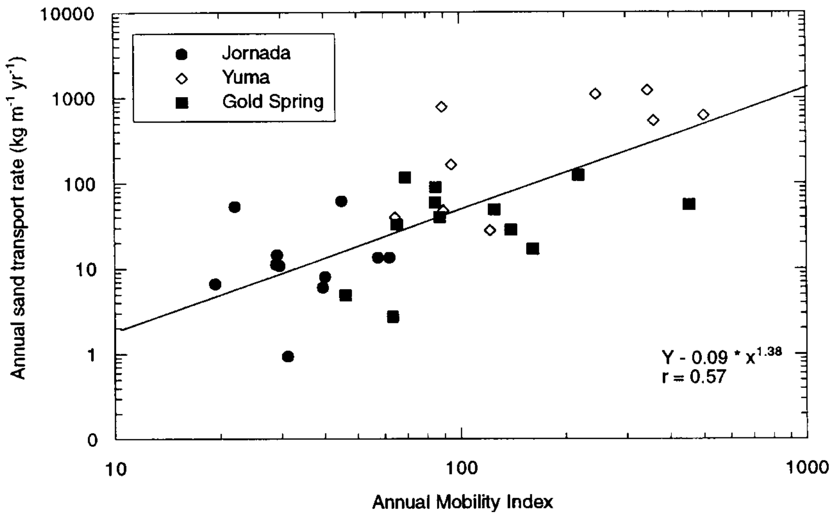


Figure 5. Relation between annual rate of sand transport and annual values of the dune mobility index

Despite the similarities between the temporal pattern of measured sand transport and calculated values of the mobility index, the degree of correlation between the data sets for individual stations is poor. The best correlation is for Yuma ($r = 0{\cdot}52$), but this is not statistically significant. When the data for all stations are aggregated, annual values of the dune mobility index and sand transport rate are moderately correlated with a high degree of scatter in the data (Figure 5). The correlation coefficient is 0·57, which is statistically significant (t-test) at the 0·01 level. There is, however, a marked improvement in the correlation coefficients between annual sand transport rate and mobility index values when the annual sand transport rate is compared to the mobility index value for the previous calendar year (Figure 6). For the complete data set, $r = 0{\cdot}78$, and for individual stations $r = 0{\cdot}68$ for Jornada, 0·88 for Yuma and 0·69 for Gold Spring. All these are statistically significant (t-test, 0·01 significance level). Although the data set is very small, there is a high degree of correlation between the mean annual values of sand transport rate and mobility index for the three stations ($r = 0{\cdot}93$). This suggests that, while the annual value of the dune mobility index is a poor indicator of the level of sand transport on a year-to-year basis, it does appear to be capable of predicting the overall level of sediment transport on a decadal or greater timescale.

DISCUSSION

Comparison of data sets for calculated values of the dune mobility index of Lancaster (1988) and measured rates of sand transport for three stations in the southwestern United States show that the index is capable of predicting the general level of aeolian activity on a timescale of decades or longer. It is therefore a valid index of aeolian activity when used in the manner for which it was originally intended.

When annual rates of sand transport are compared with calculated annual values of the mobility index, there is a high degree of scatter and a poor correlation at individual stations. Some of the data scatter may occur because the sand traps are not fully efficient or have not been regularly serviced. The latter factor is most likely at Gold Spring, where problems of access to the site in winter resulted in sporadic collection of trapped sand in many years. The data for Yuma show the highest level of correlation between calculated and measured parameters, and this site has a history of careful and regular maintenance.

Limited observation data suggest that the dune mobility index does model the physical and biological processes involved in sand transport on timescales of years to decades. All the Geomet stations have collections of repeat photography that record changes in vegetation cover from year to year. Quantification of

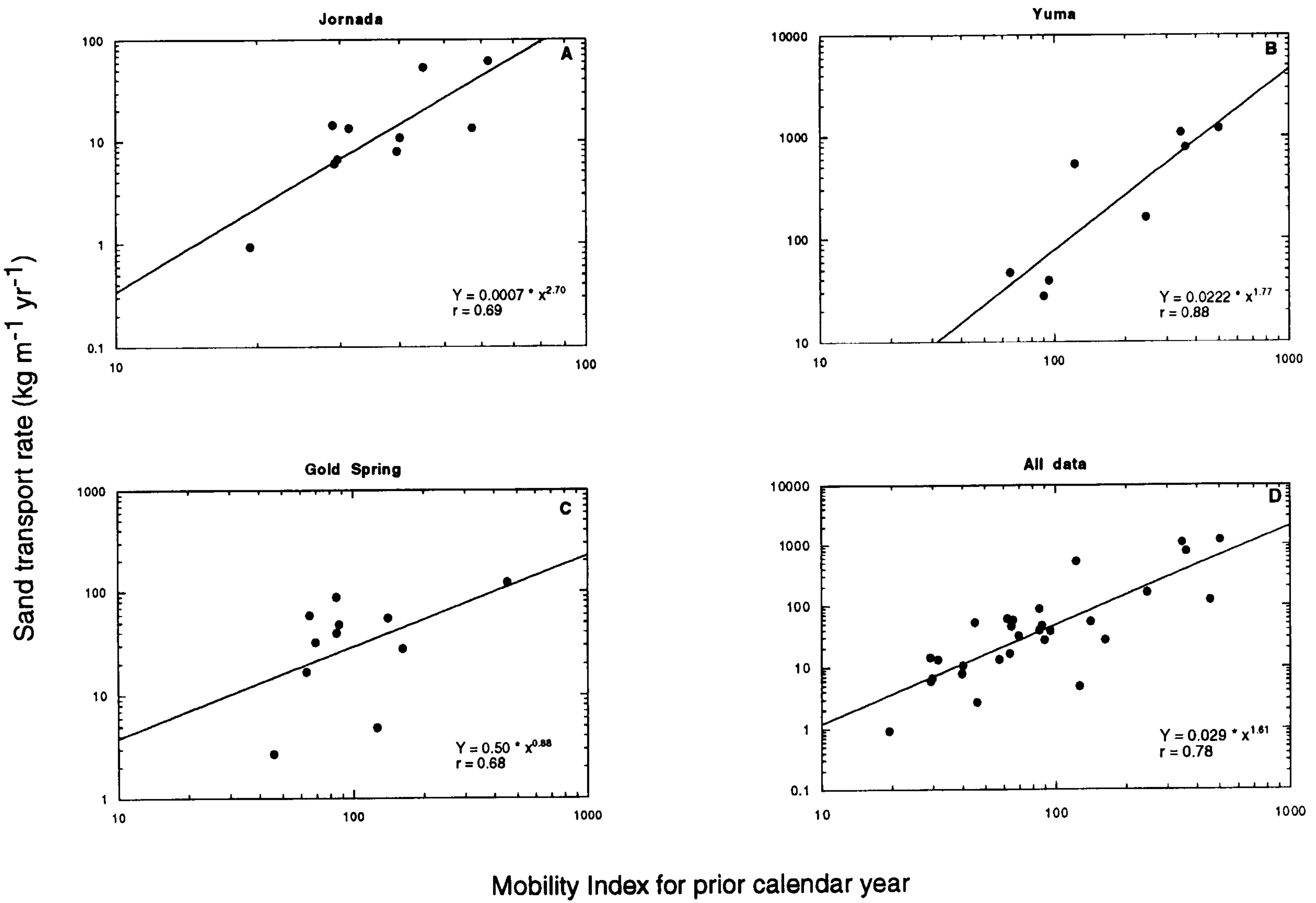
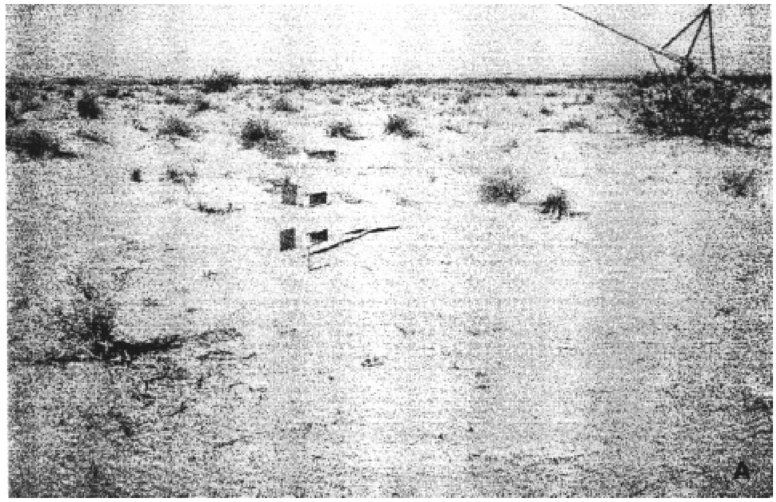


Figure 6. Relation between annual rate of sand transport and annual values of the dune mobility index for the previous year

(A)



(B)

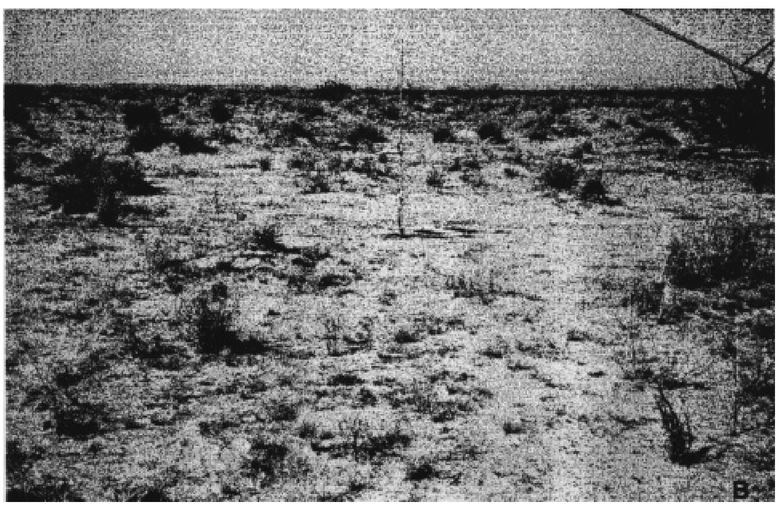


Figure 7. Ground photographs showing variations in vegetation cover at the Yuma site in years of contrasting rainfall. Both views looking west past the BSNE sand trap. (A) 12 March 1991; (B) 1 March 1993. Rainfall was 45·5 mm in 1991 and 158·4 mm in 1993

these changes is the subject of ongoing investigation, but the images in Figure 7 give a clear picture of the growth and decline of perennial and ephemeral plants at the Yuma station which reflect changes in the amount of effective precipitation. At this station, vegetation cover as measured by the lateral cover (*Lc*) (Musick and Gillette, 1990) is strongly positively correlated with annual rainfall for that year ($r = 0{\cdot}93$), and with annual mobility index values ($r = 0{\cdot}84$). Figure 8 shows clearly that the annual sand transport rate at Yuma decreases exponentially with vegetation cover, as measured by the lateral cover. This strongly suggests that the mobility index is a good index of the potential for sand movement in environments where the rate of sand movement is controlled by vegetation cover.

The mobility index is, however, based on annual totals of precipitation and potential evapotranspiration and does not reflect the seasonal distribution of precipitation, which is critical for the growth of desert plants in these environments. A further consideration is that the effects of lags between the time of precipitation and the growth or decline of plants may be important in these environments, as suggested by the improved correlation obtained between sand transport rates and the mobility index when the index is lagged by a calendar year. Similarly, dead vegetation may persist for years after rainfall events and may affect sand

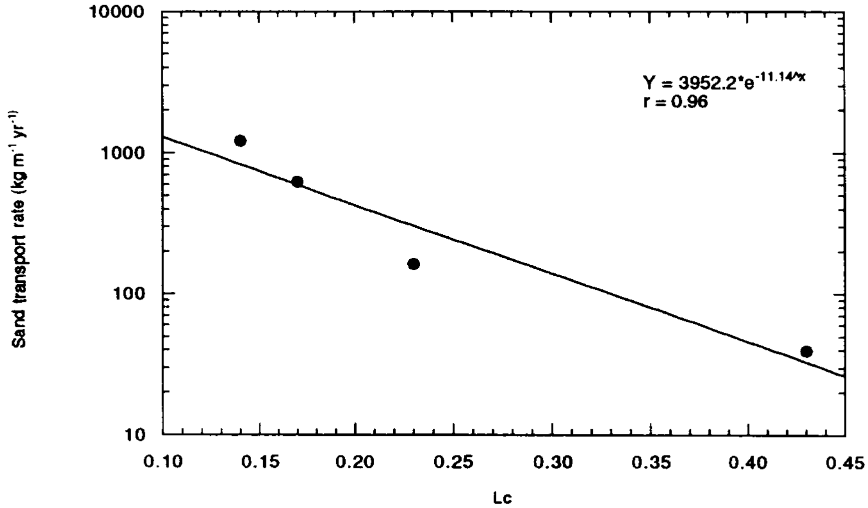


Figure 8. Relation between lateral vegetation cover (*Lc*) and sand transport rate at the Yuma site for the years 1988–1990, 1992–1993

transport at these times. This is not reflected in the index and may account for some of the lag effects observed for sand transport rates after the period of high rainfall in 1992 and 1993.

Calculation of the wind energy term in the index requires the choice of a threshold wind speed for sand transport. In this study the threshold was selected to enable comparison with values of the dune mobility index generated by Muhs and Maat (1993). The 300 μm median grain size selected is representative of surface sand at Jornada and Yuma, but not at Gold Spring, where the fine surface sand results in a threshold equivalent wind speed at 6·1 m of 4·25 m s^{-1}. The values of the mobility index are very sensitive to choice of a threshold wind speed, which effectively determines the weighting given to wind energy in the equation. Use of the lower threshold for Gold Spring results in mobility index values that average 164 over the period of record, a value that is not representative of the state of the dunes in this area.

Further, the threshold wind speed used here is calculated using equations that express threshold as a function of particle size, as determined in wind tunnel experiments. Natural transport thresholds are, however, a function of other factors including crusting and cohesion, soil moisture and vegetation cover (Gillette, 1978; McKenna-Neuman and Nickling, 1989; Stockton and Gillette, 1990 Marticorena *et al.*, 1997;). The actual transport thresholds for the Geomet stations can be estimated using data from the Sensit instrument. Data in Musick and Gillette (1990) suggest that the transport threshold for Yuma and Jornada sites is 3·2 to 3·7 times the equivalent value for an unvegetated surface. Further, transport thresholds can reasonably be expected to vary over time as a result of changes in vegetation cover, soil moisture etc. and these effects are not reflected in the index.

CONCLUSIONS

This study has shown that the dune mobility index developed by Lancaster (1988) provides a good estimate of the level of sand transport on periods of decades. It is somewhat less reliable at predicting changes in sand transport from year to year, because of the effect of lags between changes in precipitation and vegetation growth, which is the main control on sand transport in the environments studied. The index is also very sensitive to choice of a transport threshold. Therefore, future versions of this index should include a term to reflect the seasonal distribution of precipitation as well as a different term for wind energy, for example the cube of mean annual wind speed. We are currently developing these modifications to the mobility index.

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